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ATMOSPHERIC CHANNEL EFFECTS ON TERRESTRIAL FREE SPACE OPTICAL COMMUNICATION LINKS

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Abstract. *This paper illustrates the challenges imposed by the atmospheric channel on the design of a terrestrial laser communication link. The power loss due to scattering effect is described using the Kim/Kruse scattering model while the effect and the penalty imposed by atmospheric turbulence is highlighted by considering the bit error rate (BER) of an On-Off Keying modulated link in an optical Poisson channel. The power loss due to thick fog can measure over 100 dB/km while snow and rain result in much lower attenuation. We show that non-uniformity in the atmospheric temperature also contributes to performance deterioration due to scintillation effect. At a BER of 10^{-4}, for a channel with a turbulence strength of >0.1, the penalty imposed by turbulence induced fading is over 20 photoelectron counts in order to achieve the same level of performance as a channel with no fading. The work reported here is part of the EU COST actions and EU projects..*

INTRODUCTION

Terrestrial laser communication technology commonly tagged free-space optics (FSO) continues to attract attentions because it has the full potential to adequately complement the widely used radio frequency (RF) technologies within the access network [1, 2]. There has been a steady rise in the number of vendors, telecommunication service providers, businesses and institutions alike that now deploy FSO technology within their networks [2]. This increased acceptability is the direct consequence of several successful field trials in different parts of the globe. In Europe main work on FSO was done within the EU framework 6 projects and the COST actions. In latter part of 2008 a new COST action called IC0802 on “Propagation tools and data for integrated Telecommunication, Navigation and Earth Observation systems” was started and within this action, one working group (consisting of around 10 participants) is involved on optical wireless communications.

The atmosphere however poses implementation challenges that impair the availability/performance of a laser communication system. Of all weather effects, the thick fog remains the most deleterious, resulting in over 100 dB/km attenuation coefficient [2, 3]. It consequently limits the achievable link range to about 500 meters [2]. For links installed or intended to operate over a longer range during such photon extinguishing conditions, provisions should be made to route the traffic via alternative/back-up links such as the RF but at a reduced data rate. Atmospheric turbulence is another important factor that impairs the performance of an FSO system. It results in the random fluctuation of the intensity of the optical radiation that is traversing the atmospheric channel [4]. This effect is otherwise referred to as scintillation. And it is similar to the fading experienced in RF systems except that the fading is caused by the atmospheric turbulence as against multipath propagation and or frequency selectivity of the channel in RF.

In this paper, we discuss the channel effects (fog and atmospheric turbulence) and their implications for a terrestrial laser communication system. The modulation technique under consideration will be the OOK and the channel is assumed to be an ideal Poisson optical channel. This assumption is particularly useful in describing the effect of atmospheric turbulence. The rest of the paper is organized as follow. In Section 2 details of atmospheric channel attenuation due to Mie scattering and fog is presented, while Section 3 discussed the FSO link BER performance in an atmospheric turbulence channel. Concluding remarks are given in Section 4.

1. ATMOSPHERIC CHANNEL ATTENUATION

The atmospheric channel attenuates the field traversing it as result of absorption and scattering processes. The concentrations of matter in the atmosphere, which result in the signal attenuation vary spatially and temporally, and will depend on the current local weather conditions. For a terrestrial FSO link transmitting optical signal through the atmosphere, the received irradiance at a distance, L from the transmitter is related to the transmitted irradiance by the Beer-Lambert's law given as [5]:

$$\tau(\lambda, L) = \frac{P_R}{P_T} = \exp(-\gamma(\lambda), L), \qquad (1)$$

where $\gamma(\lambda)$ and P_R represent the total attenuation/extinction coefficient (m^{-1}) and the received optical power at a distance, L. P_T and $\tau(\lambda, L)$ represent the optical power at the optical source and the transmittance of the atmosphere at wavelength, λ respectively.

The attenuation of the optical signal in the atmosphere is due to the presence of molecular constituents (gases) and aerosol. The aerosol is made up of tiny particles of various shapes ranging from spherical to irregular shapes suspended in the atmosphere. The particles generally have sizes spanning from sub micrometer to a few tens of centimeters. Hence, the attenuation coefficient is the sum of the absorption and the scattering coefficients from aerosols and molecular constituents of the atmosphere [7]. It follows therefore that:

$$\gamma(\lambda) = \alpha_m(\lambda) + \alpha_a(\lambda) + \beta_m(\lambda) + \beta_a(\lambda). \qquad (2)$$

The first two terms represent the molecular and aerosol absorption coefficients, respectively while the last two terms are the molecular and aerosol scattering coefficients respectively.

Absorption takes place when there is an interaction between the propagating photons and molecules (present in the atmosphere) along its path. Some of the photons are extinguished and their energies converted into heat [8]. The absorption coefficient depends very much on the type of gas molecules and its concentration [5]. Absorption is wavelength dependent and therefore selective. This leads to the atmosphere having transparent zones-range of wavelengths with minimal absorptions-referred to as the transmission windows. However, the wavelengths used in FSO are basically chosen to coincide with the atmospheric transmission windows [9, 10], resulting in the attenuation coefficient being dominated by scattering. The attenuation is thus reduced to:

$$\gamma(\lambda) \cong \beta_a(\lambda) \qquad (3)$$

Scattering results in angular redistribution of the optical field with and without wavelength modification. The scattering effect depends on the radius, r of the particles (fog, aerosol) encountered during propagation. One way of describing this according to [2, 10] is to consider the size parameter $x_o = 2\pi r / \lambda$. If $x_o << 1$ the scattering process is classified as Rayleigh scattering [11], if $x_o \approx 1$ it is Mie scattering and for $x_o >> 1$ [12] the scattering process can then be explained using the diffraction theory (geometric optics) [7].

The scattering process for different scattering particles present in the atmosphere is summarised in Table 1.

TABLE 1 Typical atmospheric scattering particles with their radii and scattering process at λ = 850 nm

Type	Radius(μm)	Size parameter, x_o	Scattering process
Air Molecules	0.0001	0.00074	Rayleigh
Haze particle	0.01 – 1	0.074 – 7.4	Rayleigh – Mie
Fog droplet	1 – 20	7.4 – 147.8	Mie - Geometrical
Rain	100 – 10000	740 – 74000	Geometrical
Snow	1000 – 5000	7400 – 37000	Geometrical
Hail	5000 –50000	37000 – 370000	Geometrical

A. Mie scattering

The Mie scattering occurs when the particle size is comparable to the beam size. The fog particle size compares very much with the infrared wavelengths usually used in FSO thereby making fog a key contributor to optical power/irradiance attenuation. Moreover, in the wavelength band of interest in FSO (0.5 μm – 2 μm), the Mie scattering dominates. Based on the assumptions that: the scattered light has the same wavelength as the incident light, only single scattering occurs while the multiple scattering effects are neglected and that the particles are spherical in shape and are acting independently with a complex refractive index in space, [6] derived the following expression for the Mie scattering.

$$\gamma(\lambda) \cong \beta_a(\lambda) = 10^5 \int_0^\infty Q_d\left(\frac{2\pi r}{\lambda}, n'\right) \pi r^2 n(r) dr \tag{4}$$

where r (cm) is the particle (fog, aerosol etc.) radius , λ is the transmission wavelength in μm, Q_d is the Mie scattering efficiency, n' is real part of the complex refractive index and $n(r)$ is the volume concentration that is the number of fog particles per unit volume per unit increment in radius. Here, γ(λ) is the specific attenuation measured in dB/km and is calculated by summing up the attenuation effect of all the individual fog droplets present per unit volume per unit increase in radius.

However, the particles encountered in the atmosphere have complex shapes and orientations. Applying the theory of Mie scattering to these atmospheric particles is very complicated. Henceforth, our description of attenuation due to scattering will be based on reported empirical formulae. These empirical equations are often expressed in terms of the visibility range V in km. The visibility range is the distance that a parallel luminous beam travels through in the atmosphere until its intensity drops to 5% of its original value [2]; it is measured with an instrument called the transmissiometer.

The empirical model [10] is given by:

$$\beta_a(\lambda) = \frac{3.91}{V}\left(\frac{\lambda}{550}\right)^{-\delta}, \tag{5}$$

According to the Kim model, δ is given as:

$$\delta = \begin{cases} 1.6 & V > 50 \\ 1.3 & 6 < V < 50 \\ 0.16V + 0.34 & 1 < V < 6 \\ V - 0.5 & 0.5 < V < 1 \\ 0 & V < 0.5 \end{cases}. \tag{6}$$

while Kruse model defines δ as [13]:

$$\delta = \begin{cases} 1.6 & V > 50 \\ 1.3 & 6 < V < 50 \\ 0.585V^{\frac{1}{3}} & V < 6 \end{cases}. \tag{7}$$

It should be mentioned that these models were not originally developed for foggy conditions but they still give a good estimation of the attenuation of optical signals in foggy environments.

The visibility range values under different weather conditions are as presented in Table 2 [2], while Fig. 1 shows the attenuation coefficient values based on the Kim model for different visibility range values.

TABLE 2: Weather conditions and their visibility range values

Weather condition	Visibility range (m)
Thick fog	200
Moderate fog	500
Light fog	770 – 1000
Thin fog/heavy rain (25mm/hr)	1900 – 2000
Haze/medium rain (12.5mm/hr)	2800 – 40000
Clear/drizzle (0.25mm/hr)	18000 – 20000
Very clear	23000 – 50000

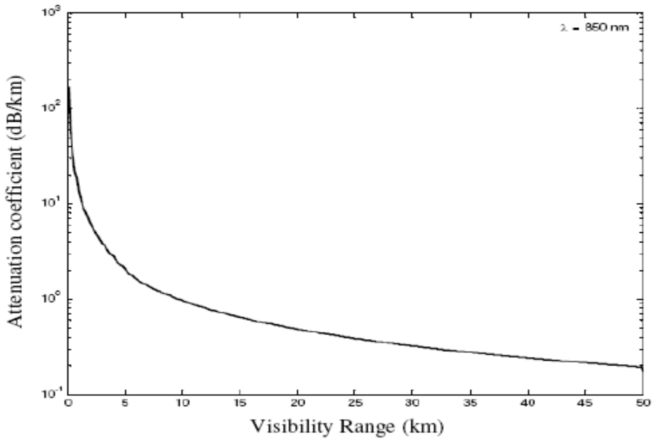

Figure. 1: Attenuation coefficient as a function of visibility range at λ = 850 nm.

We present in Figure 2 the time series of attenuation results for an FSO link operating with a laser source of 785 nm wavelength in the city of Milan. This terrestrial FSO system goes into outage every time the measured attenuation exceeds the allowable dynamic range of 21 dB (~ 66 dB/km) set for atmospheric losses.

From these data, the peak value of fog attenuation is estimated to be to 154 dB/km at a corresponding visibility of ~114 m. The changes in specific attenuations were about ± 8 dB/km averaged over a second scale [14]. This shows that optical attenuation in foggy environments poses a great challenge for a reliable operation of FSO links. In order to guarantee a reliable and 100% availability therefore, adequate link margin must be provided to account for the fog attenuation.

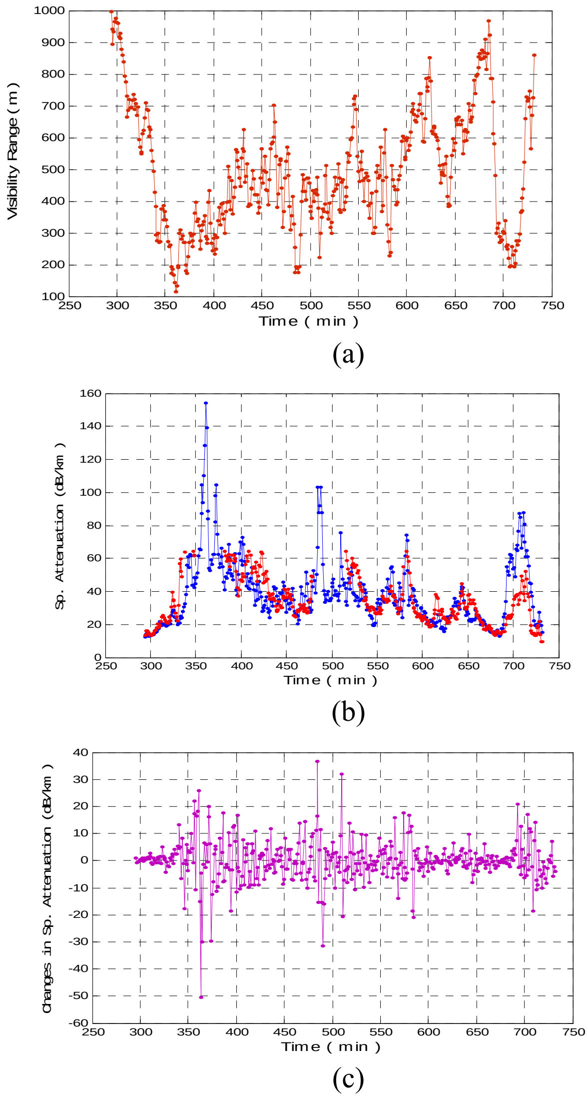

Figure. 2: Time profiles of: (a) visual range, (b) specific attenuation, and (c) differences in specific attenuation during a fog event occurred in Milan on 11th January 2005.

In (b) two profiles are shown: the measured laser attenuation (red curve) and the attenuation as estimated from visual range (blue curve). [14]

In comparison, the power loss due to snow and rain effects is much lower. But they should still be accounted for in the FSO system link margin. A typical value of specific attenuations due to rain can be between 20-30 dB/km for a rain rate of 150 mm/hr, whereas specific attenuation through falling snow can measure up to 68 dB/km [15].

2. SCINTILLATION

The atmospheric temperature at a given location is never constant, it fluctuates both in the temporal and spatial domains. The fluctuation is a function of the atmospheric wind speed and the atmospheric pressure. This small variation (0.01 to 0.1 degrees) in the air temperature brings with it, a spatial and temporal variation in the refractive index of the atmospheric optical channel. The channel thus behaves like a pathway filled with optical prisms whose sizes and refractive indices are constantly changing. The implication of this is that, the received signal irradiance/power fades in sympathy with the fluctuation of the temperature along the propagation path.

The modelling of this irradiance fluctuation has received considerable attention in literature with a number of models now in place to describe this phenomenon across different regimes [16]. In illustrating the implication of this effect on an FSO link however, we will be considering the log normal turbulence model [17] and the modulation technique will be OOK as described in the following section.

A. BER of FSO in Poisson atmospheric optical channel

Based on the received average power given by (1), the average received photoelectron count is given by:

$$\langle k \rangle = \frac{\eta \lambda T P_R}{hc}, \qquad (8)$$

where h and c are the Planck's constant and the speed of light in vacuum respectively. η is the quantum efficiency of the photodetector and T is the optical pulse duration. However, the instantaneous count k unlike the average count is not constant; it varies with time due to the following reasons:

1) The quantum nature of light/photodetection process which suggests that the instantaneous number of count k follows the discrete Poisson distribution of equation (9) with an associated quantum/photodetection noise of variance $\langle k \rangle$.

$$p(k) = \frac{\langle k \rangle^k \exp\left(-\langle k \rangle\right)}{k!}. \qquad (9)$$

2) The received signal field is randomly varying due to the effect of scintillation. This fact, combined with 1) implies that the number of count is now doubly stochastic and the probability of k counts is now given by:

$$p_1(k) = \int_0^\infty \frac{\left(\eta\lambda T P_R/hc\right)^k \exp\left(-\eta\lambda T P_R/hc\right)}{k!\sqrt{2\pi\sigma_l^2}\,P_R} \times \exp\left[-\left(\ln\frac{P_R}{P_o}+\frac{\sigma_l^2}{2}\right)^2 \Big/ 2\sigma_l^2\right] dP_R \qquad (10)$$

where P_o is the received power in the absence of atmospheric turbulence.

Considering the presence of background radiation and atmospheric turbulence, when an optical pulse is transmitted (that is bit '1' sent), a decision error occurs when the number of counts k is less than a pre-determined threshold count k_{th}. Thus, the probability of detecting bit '0' when bit'1' was transmitted is:

$$p_1(k < k_{th}) = \sum_{k=0}^{k_{th}} \int_0^\infty \frac{\left(\eta\lambda T(P_R+P_B)\right)^k \exp\left(-\eta\lambda T(P_R+P_B)/hc\right)}{(hc)^k\, k!\sqrt{2\pi\sigma_l^2}\,P_R} \times \exp\left[-\frac{1}{2\sigma_l^2}\left(\ln\frac{P_R}{P_o}+\frac{\sigma_l^2}{2}\right)^2\right] dP_R \qquad (11)$$

where P_B is the power of the background radiation that falls within the receiver's field of view and $k_b = \eta\lambda T P_B/hc$. An indicator of the strength of fading introduced to the channel due to turbulence is the log irradiance variance, σ_l^2. For the weak turbulence under consideration, its values should be less than unity.

Similarly, the probability of detecting bit '1' when bit '0' was transmitted is:

$$
\begin{aligned}
&p_0(k > k_{th}) = \\
&= \sum_{k=k_{th}}^{\infty} \frac{\left(\eta\lambda TP_B/hc\right)^k \exp\left(-\eta\lambda TP_B/hc\right)}{k!} \\
&= 1 - \sum_{k=0}^{k_{th}-1} \frac{\left(\eta\lambda TP_B/hc\right)^k \exp\left(-\eta\lambda TP_B/hc\right)}{k!}
\end{aligned}
\tag{12}
$$

It should be noted from (12) that atmospheric turbulence has no impact when no optical power is transmitted.

If the bits ‘1’and ‘0’ are assumed to be equally likely to be transmitted, then the system theoretical bit error rate (BER) becomes:

$$BER = 0.5[p_o(k > kth) + p_1(k < kth)]. \tag{13}$$

For an optimal performance, k_{th} is the value of k that satisfies expression (14). This is invoking the maximum likelihood symbol-by-symbol detection condition.

$$
\begin{aligned}
&\frac{\left(\eta\lambda\, TP_B/hc\right)^k \exp\left(-\eta\lambda\, TP_B/hc\right)}{k!} = \\
&\int_0^{\infty} \frac{\left(\eta\lambda\, T(P_R + P_B)\right)^k \exp\left(-\eta\lambda\, T(P_R + P_B)/hc\right)}{(hc)^k\, k!\sqrt{2\pi\sigma_l^2}\, P_R} \times \\
&\exp\left[-\frac{1}{2\sigma_l^2}\left(\ln\frac{P_R}{P_o} + \frac{\sigma_l^2}{2}\right)^2\right] dP_R
\end{aligned}
\tag{14}
$$

Combining (11), (12), (13) and (14), we show in Fig. 3 the impact of scintillation on the achievable BER of the system. In the figure, the BER is plotted against the average count $k_o = \eta\lambda TP_o/hc$. The penalty incurred due to scintillation is quite evident from the plot. With respect to no scintillation condition, over 20 additional photoelectron counts are needed to maintain the same BER of 10^{-4} in a channel characterised by $\sigma_l^2 > 0.1$. So when designing a terrestrial laser communication link, adequate margin based on the results shown in Fig. 3 should be made available to cater for scintillation effect… Alternatively, schemes such as multiple lasers and receiver array can be employed to mitigate this deleterious effect. Another viable means of mitigating scintillation is to use a wide receiver aperture that is several times the turbulence coherence length coupled wide divergence laser, that is, aperture averaging. It should be mentioned that the results of Fig. 3 should be seen as the theoretical performance lower bound since the photo-multiplication process present in the system is assumed ideal. In practical systems, the gain factor of the photodetector and a photo multiplier is statistically varying.

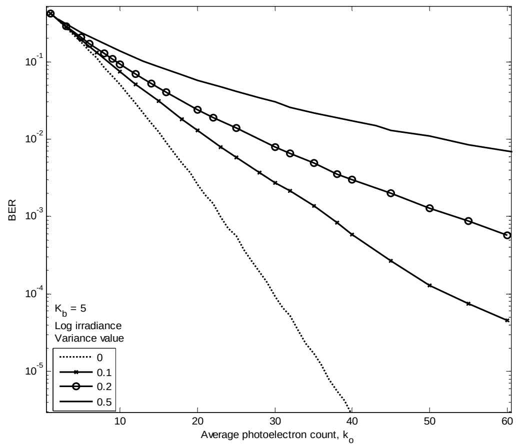

Figure. 3: BER against average photoelectron count in atmospheric turbulence channel

3. CONCLUSIONS

The challenges imposed on the design and performance of a terrestrial laser communication system have been highlighted and discussed. The presence of matter (gases, suspended particles, aerosols, fog, rain and haze) along the propagation path extinguishes and redirects the traversing photons. An attenuation factor of over 100 dB/km is possible in the presence of thick fog. The power loss due to snow and rain effects is much lower compared to that due to the thick fog. A typical value of specific attenuations due to rain is between 20-30 dB/km for a rain rate of 150 mm/h, whereas specific attenuation through falling snow can reach up to 68 dB/km. We showed the time series of attenuation results for an FSO link operating at 785 nm wavelength, illustrating that the link goes into outage every time the measured attenuation exceeds the allowable dynamic range of the receiver i.e., 21 dB (~ 66 dB/km) set for atmospheric losses. Non-uniformity in the atmospheric temperature also contributes to performance deterioration due to scintillation effect. At a BER of 10^{-4}, a channel characterised by fading strength, $\sigma_l^2 > 0.1$ is predicted to require 20 extra photoelectron counts in order to achieve the same level of performance as a channel with no fading. As such, extra margin should always be made available to counteract scintillation effect and or aperture averaging or spatial/temporal diversity techniques employed in the design of laser communication links spanning over 1 km.

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